Global agricultural trade and land system sustainability: Implications for ecosystem carbon storage, biodiversity, and human nutrition

(article starts on next page)

One Earth

Review

Global agricultural trade and land system sustainability: Implications for ecosystem carbon storage, biodiversity, and human nutrition

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SUMMARY

Global land systems are increasingly shaped by international trade of agricultural products. An increasing number of studies have quantified the implications of agricultural trade for single different aspects of land system sustainability. Bringing together studies across different sustainability dimensions, this review investigates how global agricultural trade flows have affected land systems and resulting impacts on food and nutrient availability, natural habitat conversion, biodiversity loss, and ecosystem carbon storage. We show that the effects of trade on land systems are highly heterogeneous across regions and commodities, revealing both synergies and trade-offs between improved nutrition and environmental conservation. For instance, we find that while the concentration of cereal production in North America has spared land, the increased demand for tropical products induced by trade has negatively impacted tropical ecosystems. Based on the current state of knowledge, we identify six pathways for how future research can contribute to a more comprehensive understanding of how agricultural trade can positively contribute to meeting global sustainability goals.

INTRODUCTION

Land systems encompass not only the terrestrial component of the Earth system, but also "all processes and activities related to the human use of land, including socioeconomic, technological and organizational investments and arrangements, as well as the benefits gained from land and the unintended social and ecological outcomes of societal activities."[1] Land systems are thus essential to the functioning of both social and ecological systems. Among other ecosystem services, land systems provide societies with food, material, and energy resources. At the same time, how we manage land resources has major implications for central sustainability challenges, such as the provision of sufficient and nutritious food and the climate and biodiversity crises.

In preindustrial times, most land systems were largely local systems, and trade was only a viable option for very high-value goods or between cities and their immediate hinterlands. Industrialization has opened these local systems, with trade flows between systems becoming a central component.[2] These trade flows encompass both agricultural inputs, such as fossil fuels and artificial fertilizers, which are typically traded over large distances, and the many outputs of land systems, for instance food resources exported to areas that are limited in their natural resource endowments.[3] Recently, the spatial disconnect between different components of land systems has attracted increased scholarly attention.[4,5] However, although many studies have been conducted around the topic of this spatial disconnect, most have focused on the impact of international trade on a single dimension of land systems (e.g., food availability, carbon, biodiversity, or nitrogen) or have explored telecouplings between individual, distant social-ecological systems.[4] We address this knowledge gap by jointly reviewing quantitative global studies across multiple sustainability dimensions and by providing an integrated analysis of the implications of international trade on land systems. In particular, our review focuses on food availability and habitat conversion and its effect on ecosystem carbon and biodiversity.

Since the industrial revolution, growing trade volumes have increasingly driven transformations of land systems. Looking at the major output of land systems, a body of literature has asked how trade alters the quantity and quality of food and nutrients available for human consumption around the globe. Other studies have quantified how increasing trade volumes alter ecological characteristics of land systems, which represents a central aspect of global change. International trade has been identified as a driver of recent conversions of natural habitats (e.g., deforestation). Such habitat conversions are the largest driver of biodiversity loss and they induce land-use change emissions, a

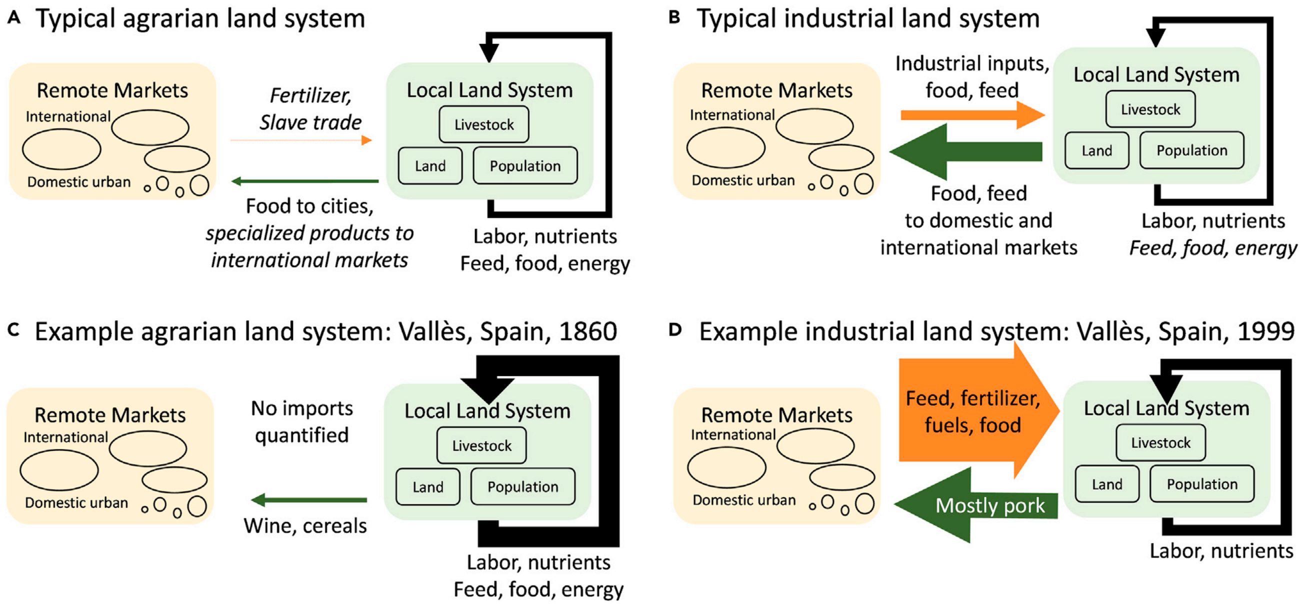


Figure 1. Schematic view of links between local land systems and remote markets

(A–D) The thickness of arrows symbolizes the approximate biophysical extent of the respective energy flows in (A) typical agrarian and (B) typical industrial globalized land systems (italic font refers to conditions for some land systems only), and in the example of Vallès County in Catalonia, Spain in (C) 1860 and (D) 1999, based on Marco et al.,[17]. Export quantities were estimated based on the assumption that in 1860 food and energy was consumed locally and only the surplus was sold, while in 1999 all production was assumed to be exported.

major component of the global carbon budget. The climate and biodiversity crises are among the major sustainability crises the global community faces today,[6] with changes within land systems being central to addressing both, as recently elaborated in assessment reports by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services and the Intergovernmental Panel on Climate Change.[7,8]

Bringing the different dimensions together in a quantitative assessment, we compile available global-level data on these issues and integrate them into a common analysis framework. Our integrated approach, discussing several major sustainability implications of international trade on global land systems, is important in light of the United Nations' sustainable development goals framework where a holistic and multi-indicator analysis is encouraged to identify trade-offs and synergies.[9] Drawing on insights from the reviewed literature and the integrated multidimensional analyses, we end this review by laying out major challenges for research that address the links between agricultural trade and land systems.

Throughout this review we take a global perspective, assessing patterns in agricultural trade and associated impacts across large spatial scales. While this assures comprehensiveness, it also implies we miss some nuance and detail that affect how these processes play out locally, in different contexts and places. The focus is largely on studies quantifying impacts of agricultural trade on nutrition and habitats; i.e., we do not cover the burgeoning literature on how to govern land use and trade in an increasingly telecoupled world (see, for instance, Friis and Nielsen[4] and references therein). In addition, other sustainability dimensions such as the impact of international trade on freshwater use, biogeochemical cycles, livelihoods, and human development were beyond the scope of our review.

AGRICULTURAL TRADE FROM PREINDUSTRIAL TO MODERN TIMES

With the industrial revolution (c. 1800 to c. 1950), international trade in agricultural commodities shifted from primarily consisting of international exchange of cultivars, denoted as the "Colombian exchange" where plant breeds, such as potatoes or tomatoes, were traded to be cultivated in remote places, to trade in crops or food commodities.[10,11] Comprehensive quantitative global assessments of trade in agricultural products during the industrial revolution are scarce,[12] but impacts of trade on land systems in this period can be inferred on the basis of fragmented evidence. During the industrial revolution, international trade in agricultural products increased steadily[13] through technological innovation, resulting in a reduction of steamboat transport costs and an expansion of railway networks[14] as well as increasing international trade liberalization.[15] The increases in agricultural trade transformed agrarian land systems around the globe in various ways, in terms of both inputs to and outputs from land systems[16] (for a schematic representation, see Figure 1).

Agricultural trade during the industrial revolution

Global agricultural trade during the industrial revolution, i.e., from the 19th century to c. 1950, contributed to increasing agricultural production and to overcoming constraints of preindustrial agricultural production and consumption.[18] Agricultural expansion in North America and Russia provided produce to domestic urban centers and to Europe.[13] Trade was already then linked to deforestation, for instance in regions of Central Europe.[15] Agricultural expansion enabled mobilizing additional soil nutrients for production.[19] In addition, trade in fertilizers included guano, or phosphorus,[20] before the production and trade in synthetic nitrogen fertilizer took off.[21]

Trade also impacted regional specialization and land-use intensification in the 19th and early 20th centuries. Regions accessible for (sea) transport specialized in early cash crops, such as cocoa, wool, or cotton in the European colonies[22–24] or wine in Mediterranean Europe.[25] The growing industrial cities of the 19th century exerted increasing pressure on their domestic hinterlands for the provision of food,[26,27] contributing to land-use intensification. At the national level, the United Kingdom was the country dominating international agricultural trade in the 19th and early 20th centuries.[28] It has been characterized as externalizing large amounts of land use in the 19th century by importing cereals while exporting mostly coal and manufactured goods.[29,30] By the beginning of the 20th century, other European countries gained importance as major importers of agricultural products,[13] as demonstrated for example in a recent quantification of net agricultural imports to Spain.[31] After World War I, Russia ceased being a major exporter of agricultural products[13] while exports from Latin America became increasingly important in the early 20th century.[32]

The "Great Acceleration" of agricultural trade

Since World War II, a new dynamic of land system change and international trade set in, part of the "Great Acceleration,"[10,11] which resulted in further—and qualitatively different—industrialization and globalization of land systems. Trade in agricultural and forestry products grew at increased rates in absolute terms, even though fossil fuels emerged as the most important material category in terms of globally traded volume.[33] The universal availability of fossil fuels lifted many of the input limitations of local land systems in large parts of the world.[18,34] Despite growing in absolute volume, trade in agricultural and forestry products declined as a fraction of total global trade, amounting for only 15% of the volume in 2010,[35] and the monetary share of agricultural products in total merchandise trade declined from 25% in 1961 to 8% in 2010.[36]

As for the outputs of land systems, cereals continued to be the major bulk commodities in agricultural trade, while feed crops, such as soybeans, gained significance in quantitative terms.[37–39] By supplying livestock production rather than final consumption, trade in feed and fodder products became a new type of major external input in some specialized industrialized local land systems.[17] In addition, specialized cash crops such as palm oil started impacting many local and regional tropical land systems, increasingly supplying global markets in recent decades (e.g., Lee et al.[40]).

Since the 1980s, less densely populated world regions such as Latin America, North America, and Australia further manifested as major supply regions providing agricultural products to densely populated regions such as Europe and, increasingly, East Asia.[38,41] While China became a major importing market of agricultural products after a shift in trade policy in the early 1980s,[42] Russia and the countries of the former Soviet Union turned from net importers to net exporters of agricultural products in the period since 1990.[43,44] This spatial pattern of agricultural products being traded from less densely populated regions to more densely populated regions, irrespective of income levels, is unique to agricultural and forestry products. Other resources tend to be exported from lower-income world regions to world regions of higher income in general.[45]

Based on global databases provided by the United Nations' Food and Agriculture Organization,[36] studies have shown that in the past three decades the amount of traded food has more than doubled, accounting for about a quarter of total global production,[46] implying that around 25% of humanity's food (caloric) requirements are fulfilled through crop product trade. Just five crops—wheat, soybean, palm oil, maize, and sugar—account for approximately 60% of traded calories and 44% of traded protein, respectively.[46] This food trade is being enabled by devoting ~20% (245 million hectares) of global harvested cropland area and ~11% of permanent pasture area (365 million hectares) to export production.[47] In addition, the average number of food trade partners per country has more than doubled in the past three decades.[46] While the United States alone contributed a quarter of traded food in 1986, this share had declined to 17% by 2009 with the emergence of Indonesia and Brazil as major exporting countries.[46] Studies have also identified the countries of origin and the amounts of individual food items imported by each country to highlight the dependency of a country on others for fulfilling the demand for individual foods domestically.[48] For example, Scheelbeek et al.[49] showed that most of the demand for fruits and vegetables in high-income countries such as the United Kingdom is met by imports from low-income countries.

AGRICULTURAL TRADE, NUTRITION, AND FOOD SECURITY

The trends described in the previous section have led to a situation where today 80% of the world's population lives in countries whose total calorie imports exceed calorie exports, highlighting the role of trade in meeting food supply.[50] For instance, North Africa and the Middle East do not produce enough food to feed their populations but fulfill their nutritional requirements through imports, while East Africa and Sahel do not achieve food sufficiency even after their food imports.[46,51] Even China and Western Europe, despite producing enough calories domestically for their population, are net food importers.[46] This is partly explained by the increasing spatial disconnect in livestock production, whereby large quantities of feed are produced far from the places where livestock are reared.[52] At the same time, some major net food exporters, namely the United States, Brazil, Argentina, Indonesia, France, Canada, and Malaysia, are able to maintain their food sufficiency even after exporting a substantial amount of food produced domestically because of high production levels in relation to their populations.

Impacts of trade on micronutrient availability

Apart from calories, humans need other macronutrients such as protein, fiber, and several essential micronutrients (vitamins and minerals) for a healthy life. Recent studies have shown that international food trade enables many countries to meet their micronutrient requirements and that a counterfactual scenario with no trade would leave millions of people malnourished in many countries.[53,54] For example, the sufficient availability of folate and zinc in Mexico, Spain, and Saudi Arabia is enabled through their food imports while the iron requirements of the Chinese population would not be met through current domestic production levels but are covered by imported food and feed.[54]

Still, over 2 billion people worldwide are currently suffering from "hidden hunger," meaning their diets are deficient in one or more essential micronutrients.[55,56] Trade does not always help address this: Clark et al.[57] point out instances where international trade agreements, such as between the United States and Mexico, have increased the supply of foods linked to obesity (e.g., corn, soybeans, sugar, snack foods, and meat products). This has contributed to deterioration of dietary quality in Mexico and increased the per capita intake of foods of health concern such as sugar, sodium, cholesterol, and saturated fats.

The structure of global food trade

While trade enables nutritional security in many countries, it also highlights their vulnerability to any future shock in international trade. Torreggiani et al.[58] identified the community structure of global food trade and found that countries tend to cluster into trading blocs for different food commodities depending upon their geopolitical relations and socio-economic conditions. For instance, in a North American cluster, Central and South America trade food with the United States and Canada. Brazil, and Argentina are found to often set up alternative communities independently. Russia is generally involved in a cluster with former Soviet Union countries and a few Middle, Eastern, and Northern African (MENA) countries such as Egypt. European Union countries mostly belong to the same cluster, which sometimes trades with the Russian cluster but rarely with the United States. East and South Asian countries, e.g., Japan, China, and India, typically belong to different food trade communities than Southeast Asian countries, e.g., Thailand, Vietnam, and the Philippines.[58]

Such community structure analyses can be used to understand the vulnerabilities of different countries to production shocks within their trade partners. For example, d'Amour et al.[59] pointed out how the unusual heat wave during 2008–2010 reduced the wheat yields and total production in Russia, which led it to restrict exports. This resulted in increased market prices for wheat across the importing nations in the Middle East, likely contributing to the Arab Spring.

Kummu et al.[60] found that the increase in supply diversity of fruit and vegetables over the period 1987–2013 came with increased dependency on imports for most countries, with some countries—such as China and Japan in Asia and Mexico, Colombia, and Venezuela in Central America—being particularly vulnerable to the future shocks in the global fruit and vegetable trade network due to a low number of import partners. Beltra-Peña et al.[61] highlight future hotspots of crop production deficits, reliance on food imports, and vulnerability to food supply shocks, and point out that most countries in Africa and the Middle East will continue to be heavily reliant on imports throughout the 21st century.

Another emerging trend linking land systems with nutritional security is the acquisition of almost 100 million hectares of global agricultural land by foreign investors and affluent countries since the early 2000s, striving to ensure future supply of food.[62] The exports from already undernourished countries are more likely to embody more agricultural land than their imports, and the imports of food-secure countries generally have higher embodied land than the imports of countries where undernourishment is prevalent. Land acquisitions therefore tend to reduce the cropland availability per capita in undernourished countries, further jeopardizing their food security.[62] Müller et al.[63] found that many of the land deals in Asia and sub-Saharan Africa increase the area efficiency of land systems but at the same time threaten local nutritional security by shifting the production away from local staples toward export-oriented crops.

CLIMATE AND BIODIVERSITY IMPACTS OF AGRICULTURAL TRADE

The previous section has highlighted how trade in agricultural products affects food and nutrient availability in various ways. In this section, we review literature focusing on ecological impacts of agricultural trade. The conversion of natural habitats, such as tropical forests, woodlands, and savannas, to cropland and pastures is a key driver of both climate change and biodiversity loss, from local to global scales.[7,8] Understanding the role of agricultural trade in driving these land-use changes is therefore key to forging effective conservation and sustainable-sourcing policies. In recent years, an increasing focus on agricultural supply-chain sustainability and zero-deforestation commitments of global agribusinesses[64,65] turned the spotlight on the links between agricultural trade flows, tropical deforestation, and the consequent impacts on climate and biodiversity.

Linking deforestation to trade

Early econometric studies trying to link (agricultural) trade to forest loss were severely hampered by lack of consistent data on deforestation and methodological challenges[66,67] and showed mixed effects of trade on forest cover. Barbier[68] and Barbier et al.[69] suggested that increased trade leads to higher deforestation by driving agricultural expansion, while López and Galinato[66] showed that the relationships between trade and deforestation were highly context dependent. On the one hand, where deforestation was mainly driven by smallholder agriculture, reduced poverty and substitution of subsistence crop production for imported commodities meant that trade helped take pressure off local forests. On the other hand, where deforestation was driven by export agriculture, an increased openness to trade tended to increase pressure on forests.

With deforestation increasingly being driven by commercial agricultural production, especially by export commodities such as soybeans, palm oil, and cash crops,[65,70] we should thus expect that agricultural trade increasingly contributes to forest loss. This is also what more recent cross-country studies find: DeFries et al.[71] and Leblois et al.[72] both showed that in the early 2000s, forest losses in the tropics were higher in countries with more agricultural exports and better terms of trade (Table 1). In line with results from these cross-country studies, Faria and Almeida[73] found that municipalities in the Brazilian Amazon that were more open to trade tended to have higher deforestation rates, even when controlling for the main drivers of deforestation, beef and soybean production.

Again, though, Leblois et al.[72] have shown how the links between trade and deforestation are heterogeneous: trade

Table 1. Overview of econometric studies assessing the role of trade in agricultural commodities in driving natural habitat loss (tropical deforestation)

Reference	Coverage: Temporal	Coverage: Geographic	Habitat loss embodied in trade
DeFries et al. (2010)[71]	2000–2005	41 tropical countries	net agricultural trade (per capita) is positively correlated with forest loss
Faria and Almeida (2016)[73]	2000–2010	Brazilian Amazon (732 municipalities)	municipalities that are more open to trade exhibit higher deforestation rates
Leblois et al. (2017)[72]	2001–2010	128 low-income countries	trade measures (openness, terms of trade and agricultural exports) are positively correlated with deforestation in high forest cover/low-income countries
Abman and Clark (2019)[74]	2001–2012	189 countries	trade liberalization through regional trade agreements drives increases in tropical deforestation through agricultural area expansion

openness primarily induces deforestation in Latin America (and not in Africa or Asia) where commercial agriculture is a key driver of forest loss. Increases in agricultural exports drive deforestation mainly in countries with large remaining forest areas (i.e., countries in the early stages of the forest transition) and not in forest-scarce countries. That increased agricultural trade drives agricultural expansion and associated forest loss (and not the opposite) is corroborated by Abman and Lundberg,[74] who showed that trade liberalization through regional trade agreements on average increased forest loss in tropical low-income countries by 48% in the 3 years following their enactment.

Quantifying embodied deforestation

While econometric analyses provide evidence on a general link between agricultural commodity trade and tropical forest loss, these studies do not give any detail on the commodities driving deforestation in different places, nor do they quantify the associated environmental impacts embodied in agricultural trade. Recent analyses based on combinations of remote sensing data, agricultural statistics, and trade models are starting to shed light on these issues.

These studies have confirmed the general picture that agricultural trade is a significant driver of deforestation due to land expansion. Pendrill et al.[75] estimate that on average 40% of all deforestation due to cropland expansion was embodied in trade in 2005–2013. As seen in Table 2, for export commodities such as soybeans and palm oil, international demand represents a much larger share (60% and above). Although demand for beef is primarily domestic in Latin America, due to the outsized role of pasture expansion in driving deforestation, forest loss and associated carbon emissions embodied in beef exports from this region still rival or exceed those from soy, constituting nearly a fifth of all deforestation embodied in global agricultural trade.[76]

In absolute numbers, exports of beef, soybeans, and palm oil from a handful of countries in Latin America and Southeast Asia are linked to deforestation of hundreds of thousands of hectares annually. On the consumption side, China and the European Union play a central role, being major importers of deforestation embodied in both soybeans and beef from Latin America as well as palm oil from Southeast Asia.[76,78,79,82,84] Russia and Middle Eastern countries are also major importers of deforestation attributed to Latin American beef,[76,78] while India and other Asian countries are major importers of palm oil deforestation embodied in exports from mainly Malaysia and Indonesia.[76,79] Overall, trade in embodied deforestation tends to flow from countries with rapidly declining forest resources to countries that have passed the forest transition, and thus the increases in domestic forest areas in the latter are to some extent facilitated by the outsourcing of agricultural production.[75]

While studies quantifying the link between agricultural trade and deforestation agree on overall patterns, in terms of main commodities implicated and key sourcing and consumer regions, there are still large differences in estimates of deforestation embodied in trade across studies (see Table 2). Partly this is due to temporal trends (e.g., the rapid decrease in overall deforestation in Brazil post 2004), which result in different findings for different base years. Partly the differences reflect methodological choices (e.g., choice of amortization period over which deforestation is allocated to agricultural production).[86,87] In addition, data limitations still prevail: despite great advances in remote sensing improving our understanding of land-cover changes (e.g., Hansen et al.[88]), lack of global datasets distinguishing between different agricultural land uses limits our ability to consistently attribute forest loss to drivers across scales.[89] To overcome this data gap, many studies still rely on more or less simplistic assumptions or land-use change models to attribute deforestation to agricultural commodity production and trade (Table 2). These data limitations also explain why quantitative evidence on deforestation embodied in agricultural trade is concentrated on a few commodities (primarily beef and soy) and countries (primarily Brazil) where data availability is better.

Carbon emissions from land-use change embodied in trade

The carbon emissions due to deforestation embodied in agricultural trade flows are substantial: Pendrill et al.[76] estimate these emissions to nearly 1 Gt of CO_2 annually, constituting around a tenth of total food system greenhouse gas emissions.[90,91] This implies that for major importers of embodied deforestation, these emissions also constitute a substantial share of the climate impact of food consumption. In the European Union, for instance, carbon emissions from deforestation are estimated to account for between 13% and 30% of the carbon footprint of the average diet.[76,92]

Table 2. Overview of studies quantifying the role of trade in agricultural commodities in driving natural habitat loss and associated carbon emissions

	Coverage					
Reference	Temporal	Geographic	Commodity	Approach to linking trade to impacts	Habitat loss embodied in trade	Carbon emissions embodied in trade
Saikku et al. (2012)[77]	2007	Brazil, Indonesia	all agricultural commodities	all deforestation attributed to agricultural production based on harvested area	–	Brazil: 594 $MtCO_2$/year (32%) Indonesia: 638 $MtCO_2$/year (15%)
Karstensen et al. (2013)[78]	1990–2010	Brazil (Legal Amazon)	beef, soybeans	simple assumptions based on literature	–	beef: 75–150 MtCO–2/year (12%–19%) soy: 50–300 MtCO–2/year (33%–69%)
Henders et al. (2015)[79]	2000–2011	Argentina, Bolivia, Brazil, Indonesia, Malaysia, Papua New Guinea, Paraguay	beef, soybeans, palm oil	based on remote sensing studies and agricultural statistics	beef: 205–577 kha/year (7%–21%) soy: 205–538 kha/year (70%–87%) palm oil: 99–293 kha/year (52%–68%)	beef: 70–227 $MtCO_2$/year (7%–22%) soy: 46–112 $MtCO_2$ (68%–85%) palm oil: 65–196 $MtCO_2$/year (51%–64%)
Caro et al. (2018)[80]	2008–2012	Brazil	pork, poultry (through embodied soybean feed)	all soy feed used in meat production assumed to come from deforested land (based on Flynn et al., 2012)[81]	–	pork: 4.6 $MtCO_2$/year (17%) poultry: 1.6 $MtCO_2$ (39%)
Pendrill et al. (2019)[75]	2005–2013	156 countries (tropics and sub-tropics)	all crops, beef	land-balance model based on remote sensing data and agricultural statistics	crops: 968 kha/year (40%) beef: 250 kha/year (11%)	–
Pendrill et al. (2019)[76]	2010–2014	106 tropical countries	all crops, beef		–	crops: 764 $MtCO_2$/year (54%) beef: 197 $MtCO_2$/year (22%)
zu Ermgassen et al. (2020a)[82]	2006–2017	Brazil	soybeans	remote sensing data on forest loss and soybean cropland area	soy: 41–167 kha/year (66%–84%)	–
Escobar et al. (2020)[83]	2010–2015	Brazil	soybeans		–	soy: 75 $MtCO_2$/year
zu Ermgassen et al. (2020)[84]	2015–2017	Brazil	beef	remote sensing data on forest loss and pasture	beef: 73–75 kha/year (14%–15%)	–
Johansson et al. (2020)[85]	1987–2017	Cambodia	cassava, corn, jatropha, palm oil, rice, rubber, sugar cane, wood	remote sensing and land concession data, coupled to vegetation model	–	rubber: 2.1 $MtCO_2$/year (71%) sugar cane: 0.9 $MtCO_2$/year (74%) wood: 0.7 $MtCO_2$/year (100%) other crops: 0.5 $MtCO_2$/year (73%)

A different perspective on the impact of agricultural trade on ecosystem carbon is provided by Marques et al.[93] and Yang and Tan,[94] who estimate the carbon sequestration forgone by agricultural production and consumption by comparing current land-use patterns with a scenario where land under crop production or pasture would be allowed to naturally regenerate. These studies estimate that in ~2010 agricultural trade contributed to forgone carbon sequestration by between 2 and 11 $GtCO_2$ per year, with differences partly reflecting divergent assumptions regarding the time and speed over which the sequestration would occur should production and trade cease. While carbon emissions from deforestation originate from the tropics, where agricultural expansion is ongoing, carbon sequestration forgone due to agricultural trade is allocated to all production systems on potentially carbon-rich lands, irrespective when land conversion has taken place. As a consequence, the carbon losses due to forgone sequestration are spread more evenly around the globe. At the same time, the European Union, Asia, and the Middle East remain regions that import this environmental impact.[93,94]

Biodiversity impacts embodied in agricultural trade

The consequences of international trade flows for biodiversity are being increasingly studied. Pioneering studies have shown that international trade drives between 14% and 30% of total biodiversity impacts.[95,96] Lenzen et al.[95] were the first to present the impacts of international trade on biodiversity by linking economic multi-region input-output tables with data on threats affecting species in different countries. They found that around 30% of species threats were driven by international trade, with many of these threats being associated with the trade of agricultural and forestry-related products from low-income to high-income countries. The number of threats embodied in international trade informs on the amount of pressures affecting the species but does not provide a direct measure of the biodiversity loss.

Subsequent studies quantified the role of international trade in driving biodiversity loss using alternative metrics, leading to different results (Table 3 and Table S1). Chaudhary and Kastner[48] calculated the potential vertebrate species extinctions (i.e., mammals, birds, amphibians, and reptile species committed to extinction) that can be attributed to land use embodied in trade flows of individual crop items between different countries. They found that the relative ranking of trade flows in terms of embodied biodiversity impacts varies depending upon whether the regional or global (endemic) species extinctions metric is used (Table S1). The ranking of trade flows in terms of biodiversity impacts also depends upon which taxa are under consideration.[48,97] This variability in results due to the use of different biodiversity metrics and models reflects the multi-dimensional nature of biodiversity and the complexity of its quantification.[98–100]

Other biodiversity metrics have also been used to understand the role of international trade in driving biodiversity impacts. Kitzes et al.[101] estimated biodiversity impacts in terms of occupied bird ranges and missing individual birds, and found that approximately 23% of the impacts on biodiversity are driven by international trade. Wilting et al.[96] showed that the international trade of agricultural and forestry activities accounted for approximately 14% of total loss in mean species abundance (MSA). MSA is a metric of local biodiversity intactness and measures changes in mean abundance of original species in disturbed conditions relative to their abundance in undisturbed habitat.[105]

Studies focusing on specific commodities or regions offer more detailed insights into the role of international trade driving biodiversity impacts. Green et al.[102] studied how international trade of soy drove biodiversity impacts in the Brazilian Cerrado with great spatial detail and at the level of individual species. For example, they linked the European Union's and China's soybean consumption to recent habitat losses for the giant anteater in the Mato Grosso state. Wilting et al.[103] investigated the proportion of biodiversity impacts driven by trade in the European Union at subnational level and revealed strong differences at this level. For example, for Spain's region of Extremadura 44% of total biodiversity impacts from consumption were embodied in trade from the rest of the world and 20% embodied in intra-European Union trade. For Catalonia, 16% of total biodiversity impacts from consumption were embodied in trade from the rest of the world and 17% embodied in intra-European Union trade.

The agricultural commodities whose trade has been identified as driving the highest biodiversity impacts are coffee, tea, cocoa, beef, wood pulp, palm oil, rubber, soy, fruits, and vegetables.[48,95,102] Although certain staple crops such as rice, and cassava are also strongly linked with deforestation and biodiversity impacts, they are not heavily traded internationally. As with the overall importance of agricultural trade, over time the role of trade as a driver of biodiversity impacts has increased, with countries in the Asia and Pacific, Africa, and Middle East regions becoming more relevant as importers of biodiversity impacts embodied in international trade.[93] An analysis focusing on the income level of different countries showed similar trends, with low-income and middle-income countries showing the highest increases in the import share of their biodiversity footprints.[104]

DISENTANGLING THE EFFECTS OF TRADE ON SUSTAINABILITY

The previous sections have highlighted that the increasing trade flows have been linked to positive or negative impacts on human nutrition and, through natural habitat loss, to negative impacts on carbon storage and biodiversity. Despite increasing availability of data and global studies, assessing the overall effect of agricultural trade on land systems outcomes is far from straightforward. Due to the complex inter-relations within and across systems, we are missing a scenario of how agricultural production and land use would look without these trade flows. To quantify the effects of trade, simple counterfactuals are often used that keep all factors constant but assume that imported products are produced locally in the importing countries with their respective efficiencies.[106]

To provide a quantitative assessment of the positive and negative role played by international trade across different indicators, we employ, based on published data, such a counterfactual approach that compares the situation in 2010 with such a hypothetical no-trade scenario. This serves as a joint analysis on the effects of trade on the sustainability dimensions discussed in the previous sections and to highlight the complexities associated with assessing the sustainability of trade patterns. We combine data for the year 2010 on (1) global maps on the extent of croplands and crop products, broken down into 42 crop types,[107] (2) trade data that link crop production to countries where the crop products

Table 3. Overview of studies quantifying the role of trade in agricultural commodities in driving biodiversity loss

Reference	Coverage			Approach to linking trade to impacts	Biodiversity loss embodied in trade
	Temporal	Geographic	Commodity		
Lenzen et al. (2012)[95]	2000	187 countries	15,909 sectors	attribution of biodiversity threats to industry sectors	biodiversity threats used as a proxy for impacts on biodiversity 30% of global species threats due to international trade
Chaudhary and Kastner (2016)[48]	2011	184 countries	170 crops	countryside species-area relationship to related land-use area and impacts on species richness	regional and global impacts on biodiversity measured as potential species extinctions 17% of global biodiversity loss due to international trade
Kiztes et al. (2017)[101]	2007	129 regions	57 sectors	bird ranges and bird densities linked to a map of Human Appropriation of Primary Productivity and a map of land use	impacts measured as occupied bird ranges and missing individual birds 23% of occupied bird ranges and missing birds due to international trade
Wilting et al. (2017)[96]	2007	45 regions	48 sectors	loss in mean species abundance (MSA) due to land use, urban infrastructure, roads, and climate change	impacts on biodiversity quantified as loss of MSA 16% of MSA loss due to international trade
Chaudhary and Brooks (2019)[97]	2007	129 regions	four land-use types (agricultural, pasture, urban, forestry)	countryside species-area relationship to related land-use area and impacts on species richness	projected global species extinctions 25% of global species extinctions due to international trade
Green et al. (2019)[102]	2000–2011	Brazil (Cerrado)	soy	soy expansion maps linked with suitable habitat models	impacts computed as a "conservation score" that captures the non-linear cumulative effect of historical habitat loss on the local persistence of a species
Marques et al. (2019)[93]	2000–2011	49 regions	200 products	countryside species-area relationship to related land-use area and impacts on birds species richness	global impacts on biodiversity measured as potential bird species extinctions 22% of potential extinctions due to international trade in 2000 and 25% in 2011
Wilting et al. (2021)[103]	2010	162 regions in European Union 14 other countries/ world regions	18 sectors	loss in MSA due to land use, urban infrastructure, roads, fragmentation, and climate change	impacts on biodiversity quantified as loss of MSA
Bjelle et al. (2021)[104]	1995–2015	214 countries	200 sectors	LC-IMPACT characterization factors of biodiversity impacts from land use (based on countryside species-area relationship)	impacts on biodiversity quantified as potentially disappeared fraction (PDF) of species 19% of global PDF due to international trade in 1995 and 33% in 2015

are consumed,[36,41,75] and (3) data on the impacts of crop production on deforestation, biodiversity, and carbon storage.[76,93,108] The procedure of how the different datasets were merged for the presented analyses in Figures 2, 3, 4, and the figure accompanying Box 1 is described in experimental procedures.

The net effect of global agricultural trade

Maps of the "net trade" balances, i.e., imports minus exports, highlight that trade patterns can be very different, depending on the metric in focus. While trade in terms of calories flows largely from regions with lower population densities (Americas, Australia) to more densely populated regions with lower land availability, impacts such as deforestation and species loss are concentrated in the tropics, and most countries outside the tropics are "net importers" of these impacts.

There are indications that international food trade has contributed to lowering the total agricultural land demand compared with a counterfactual no-trade scenario. Based on data for

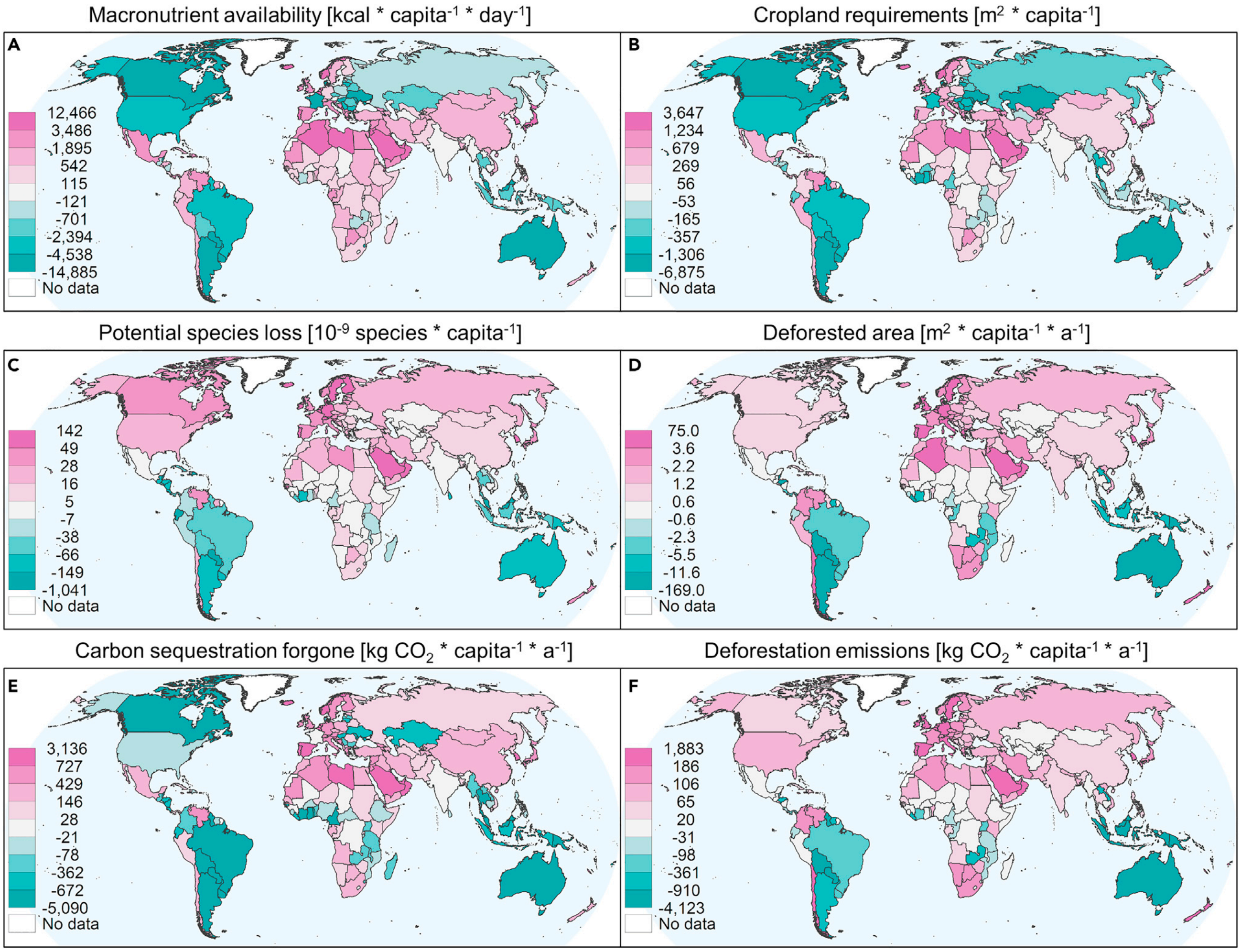


Figure 2. Per capita "net trade" balances for crop products and environmental pressures embodied in them, based on national level data for the year 2010

(A–F) The balance is calculated as imports minus exports. (A) kcal availability, (B) cropland requirements, (C) potential global species loss induced by crop production, (D) deforested area attributed to cropland expansion, (E) carbon sequestration forgone due to crop production, and (F) land-use change emissions attributed to cropland expansion. Net importers are shown in purple and net exporters in turquoise. For data sources and how the data were compiled, see experimental procedures.

2008, total cropland use was estimated 88 Mha (or 7%) higher if food imports had been substituted by domestic production (for imported products that were also grown domestically).[41] That is, because trade tends to flow from countries with higher yields for the traded product to countries with lower yields, there is a land-sparing effect of trade. Roughly half of this land-sparing effect is due to differences in agricultural management, and roughly half due to better growing conditions in the exporting countries.[41] This finding complements the existing evidence that food imports have been widely used to overcome the scarcity of land and water in several importing countries.[3]

Surprisingly, our analyses based on available global-level data suggest that this land-sparing effect of agricultural trade also translates into a net avoidance of environmental pressures linked to habitat conversion globally. Using data on potential carbon sequestration forgone and potential global species loss due to cropland use,[93,108] Figure 3 shows that the net effect of crop commodity trade on carbon storage and biodiversity is currently positive, i.e., global impacts on carbon storage and biodiversity are currently smaller compared with a no-trade situation, whereby traded products were produced in the importing country, assuming current crop yields. For importing countries and for crops that could be grown domestically, this implies, on average, not only lower domestic cropland productivity for the traded commodities but also, on average, higher domestic environmental impacts, on biodiversity and carbon storage, per unit crop product. These differences are to a large extent explained by yield differences but can also come about through differences in impacts per unit of cropland used.

For instance, we find a very large amount of avoided biodiversity impacts through current trade flows from North America to Central America and the Caribbean (Figure 3). This can partly be explained by the fact that countries in Central America and the Caribbean are home to many endemic species, which is considered in the factors we used to assess potential global species loss.[108] At the same time, Figure 3 highlights that the effects

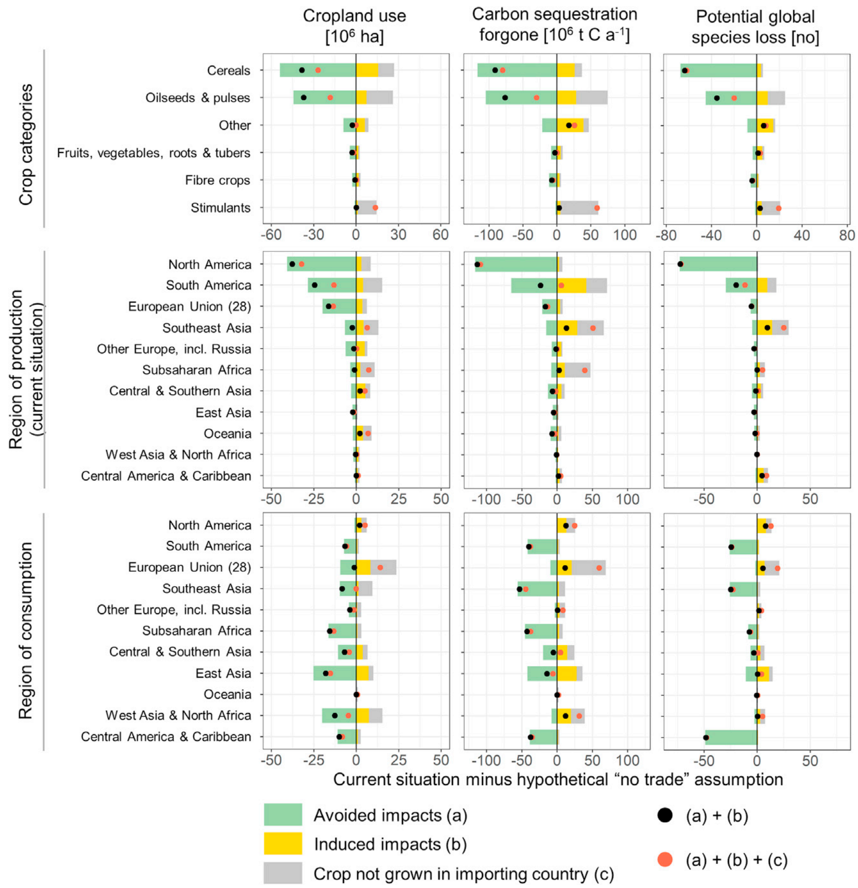


Figure 3. Differences of environmental impacts of current trade patterns versus a hypothetical "no-trade" assumption

The difference is shown for cropland use, forgone carbon sequestration, and potential species loss, and compares agricultural trade patterns in 2010 with a no-trade counterfactual. Results are aggregated over crop categories, regions where the traded crops are currently produced and exported from, and regions where the crops are imported to and consumed. The no-trade counterfactual assumes that imported crops are produced domestically with the importing country's current efficiencies and that overall demand stays constant. Cases where the exporting country's efficiencies are higher than the importing country's efficiencies are labeled "avoided impacts," as the impacts with current trade patterns are lower compared to the no-trade assumption. The opposite cases are labeled "induced impacts:" here current trade patterns lead to higher impacts than the no-trade assumption. Cases where the traded crop is not grown in the importing country are presented as gray segments of the bar, matching the current situation. We present this on the side of the additional impacts of the current situation compared with the no-trade assumption, as it is not clear whether demand for these products would exist without trade. Refer to the text for details and important caveats to be kept in mind when looking at this comparison. For data sources and how the data were compiled, see experimental procedures.

are not uniformly distributed across crops or world regions. For instance, current import patterns of the European Union induce rather than avoid impacts.

Decomposing the net impacts of trade

Our counterfactual analysis highlights the net land-sparing effect of agricultural trade. However, this is only one of the mechanisms through which increased trade affects the environment. Typically, the effect of trade on the environment is decomposed into a scale, composition, and technique effect.[119,120] That is, trade affects not only how things are produced and the associated environmental impacts (technique—discussed in the paragraphs above), but also what (composition) and how much (scale) we consume. Thus, to assess the full impact of agricultural trade on land use, carbon storage, biodiversity, and other ecosystem services, the latter two effects should also be accounted for.

Starting with the composition effect, it is clear that agricultural trade has changed what we eat: roughly one-third of agricultural trade is in commodities not produced in the importing country,[41] and there are large carbon and biodiversity impacts associated with those trade flows (gray segments in Figure 3). For instance, international trade has promoted the consumption of discretionary commodities[121] such as chocolate, coffee, and tea in temperate, high-income countries where these crops cannot be grown, causing environmental damage in exporting low-income, tropical countries. Accounting for these impacts reduces the positive global net effects displayed in Figure 3 for land area, carbon sequestration, and biodiversity by 60%, 80%, and 40%, respectively. While some of this consumption would have been substituted for other domestic produce in the hypothetical absence of international trade, and some of this production would instead have been consumed in the countries of production, it seems likely that trade has contributed to increasing demand for and environmental impacts from the cultivation of these commodities.

Moving on to the scale effect, the question is whether the efficiency increases brought about by current trade patterns are outweighed by the increased demand that this trade creates through lower agricultural prices. There is mixed evidence on such a rebound effect in agriculture, but increased agricultural productivity tends to lead to increases in cropland area (i.e., the scale effect dominates over the technique effect) for countries with large agricultural exports[122] or for crops that are primarily exported,[123] while for staple cereals productivity increases tend to translate to land sparing (i.e., the technique effect dominates over the scale effect).

To summarize, existing empirical evidence suggests that agricultural trade might have a positive effect on land demand, carbon sequestration, and biodiversity by enabling the concentration of agricultural production with intensive management systems and high yields. However, these positive effects have partly been offset by the increases in demand enabled by trade, in particular for certain cash crops such as coffee and cocoa that satisfy discretionary consumption.[121]

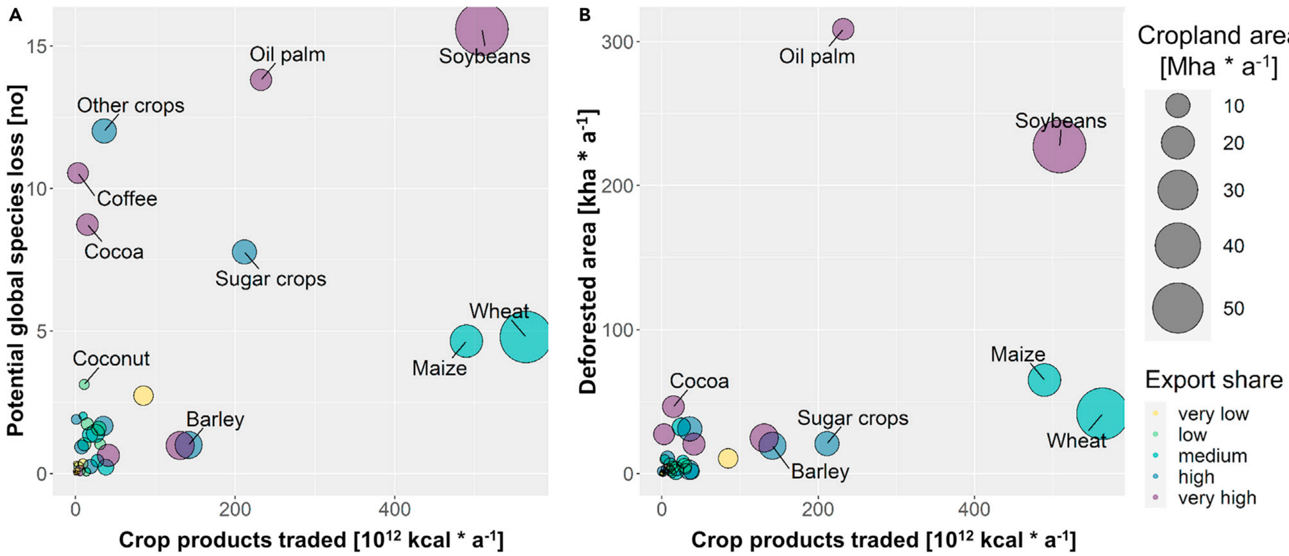


Figure 4. Relation between internationally traded crop production and potential global species loss and deforestation area attributed to cropland expansion

The bubble size indicates the amount of cropland area required for the production of the traded products; the bubble color indicates the share of global crop production that is used for exports. For data sources and how the data were compiled, see experimental procedures.

An illustrative example of the potential interplay of the different effects discussed in this section is trade in vegetable oils: Többen et al.[124] show that between 2000 and 2010, domestic vegetable oils production in Europe, China, and the United States was substituted with imported oils from biodiverse countries, specifically Indonesian palm oil and Brazilian soybean oil (composition effect). Due to the higher number of species per unit area in the exporting tropical countries, the net impact of increasing palm and soybean oil trade on global biodiversity is negative (see also Figure 3). Despite the higher yields of these oils and decreasing biodiversity impacts per unit over time (technique effect), Marques et al.[93] found that economic growth led to increasing consumption as vegetable oils have high price elasticities, especially for industrial uses,[125] which in turn translated into higher impacts on biodiversity.

The heterogeneous impacts of agricultural trade

While the numbers we compiled cover a range of land system sustainability dimensions, drawing conclusions from this tentative evidence on the role of trade in sparing land for nature should be done with caution. While land sparing can have positive environmental net effects, concentrating agricultural production in high-intensity systems also has negative effects in the form of eutrophication impacts, water scarcity, and biodiversity impacts other than the ones from habitat conversion, as well as introducing social problems.[126,127] We highlight one such potentially negative effect in Box 1 by investigating differences in crop diversity across cropland areas serving export production and cropland areas serving domestic consumption.

Importantly, even if the global net effect of agricultural trade is positive (as for the environmental indicators assessed here and within the assumptions of the analysis), the aim should still be to mitigate the negative effects of trade and to exploit its positive potential. Doing so requires an understanding of the current heterogeneity in impacts. Figure 3 clearly shows that the land, carbon, and biodiversity sparing effects are not uniform across crop groups: for cereals, where some key exporters are less carbon and biodiversity rich (e.g., the United States), avoided impacts clearly dominate over induced ones, while for the “other” crop group, which includes cash crops grown in biodiverse and carbon-rich tropical countries, current trade patterns induce additional impacts. In addition, for the category of stimulants, made up of coffee, tea, and cocoa, we find that trade in these crops is associated with considerable impacts, but the importing countries are largely located in the Global North where their cultivation is not feasible (Figure 3).

Overall, these numbers imply that the trade-offs between the effects of agricultural trade on environment and nutrition look very different for different agricultural commodities: for staple cereals, increased trade volumes have been particularly important for nutritional gains,[54] and there are also large positive carbon and biodiversity effects from this trade (see Figure 3). Here, the rebound (scale) effect is also likely small.[123] This implies that for traded cereal crops, the biodiversity and carbon impacts are relatively small compared with the amount of calories their trade provides, suggesting a “win-win” situation (Figure 4). Note that this result might not hold true if instead of calories the embodied amounts of micronutrients (e.g., vitamins and minerals) were considered. This is because the staple cereal crops either completely lack or have low amounts of micronutrients per unit weight. The trade-off between embodied environmental impacts and embodied nutrition for a particular commodity depends heavily on which nutrient is considered. In our empirical analysis we could only include traded calories, as we limited our analyses here to available data.

Conversely, for cash-crop commodities such as palm oil, coffee, and cocoa, the nutritional benefits are small and the environmental impacts of trade are large (Figures 3 and 4). In Figure 4,

Box 1. Crop diversity and international trade

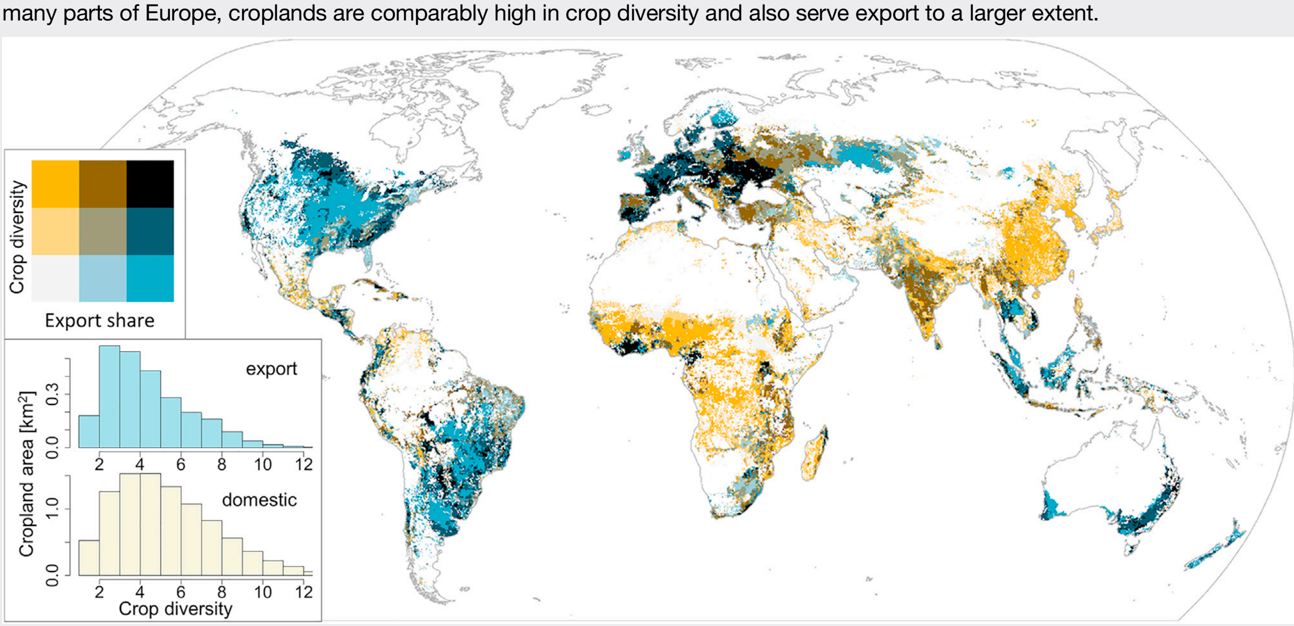
Over the past decades, crop supply across countries has become more varied while the diversity of crops grown within countries has been largely homogenized.[109] At the same time, crop diversity has recently been identified as an important driver of the stability of crop production.[110–112] High crop diversity also enhances other important ecosystem functions and services, such as soil functioning[113] and soil health,[114] and recent studies suggest that increasing crop heterogeneity within countries represents a potential lever to increase synergies between food production and biodiversity conservation.[115]

We make use of the spatial explicitness of the data compiled for this review (main text and supplemental information) and analyze relationships between global crop diversity and crop product trade. We assess differences in crop diversity across areas producing for domestic consumption and areas dedicated to export production. To do so, we assess the crop diversity at a 10 × 10 km grid globally, expressed as the exponential of the Shannon index[116] of crop types, hereafter referred to as "crop diversity." We differentiated the 42 crop types for which information on their spatial distribution in 2010 is available.[107] We calculated the Shannon index as

$$\text{Shannon index} = \sum_{i}^{N} (p_i \ln[p_i])$$

, where p_i is the proportion of area dedicated to crop i and N is the total number of crop types. The Shannon index weights each crop type in a specific area by the proportion of total area dedicated to this specific crop type. We then used the exponential of this index to express the crop diversity as linear data.[112] High crop diversity therefore corresponds to a high number of crop types grown, evenly abundant in the area considered. Finally, we calculated the mean crop diversity index across countries and crop types, weighted by cropland area in each pixel, differentiating areas dedicated to domestic production and areas dedicated to export production, and explored the distribution of this averaged index.

A Wilcoxon rank-sum test[117] showed that areas that were used for the production of exported goods were significantly less diverse (mean crop diversity index 4.39) than areas producing crops for domestic consumption (mean crop diversity index 5.28, $W = 2.65 \times 10^{11}$, $p < 0.001$). This difference is also evident from the histograms in the accompanying figure, which visualizes the relation between crop diversity and cropland use for export production. Yellow areas exhibit high crop diversity (expressed as exponential of the Shannon index) and a low share of cropland area serving export production. Blue areas harbor low crop diversity and are used for export production to a large extent. Black areas are both high in export production and crop diversity. The inset on the lower left of the figure shows histograms of distribution of crop diversity across areas used for export production (export) versus areas used for the production for products not traded internationally (domestic). The figure highlights that there are large areas in the Americas, Southeast Asia, and Australia that exhibit low crop diversity and that a high share of cropland serves export production. In contrast, many parts of Sub-Saharan Africa and China have high values of crop diversity but a low share of cropland area serving export production. In many parts of Europe, croplands are comparably high in crop diversity and also serve export to a larger extent.



Our results highlight that, while current trade patterns increase global area efficiency (see main text), exports rely on croplands with lower crop diversity. Agricultural areas dedicated to export production are indeed often dominated by large-scale industrial

(Continued on next page)

Box 1. *Continued*

monocultures.[118] Reduced crop heterogeneity may have large negative implications for the maintainance of sustainable production and the protection of important ecosystem services.[113] These results point to the importance of a nuanced and multifaceted perspective when discussing effects of international trade on land systems. Since lower crop diversity jeopardizes the stability of crop production,[112] the potential of supply shocks perpetuating through international trade networks will be increased for products originating from less crop-diverse lands. In addition, there is now growing recognition that crop heterogeneity within countries is an essential lever to maintain local biodiversity[115] and ecosystem functioning.[113,114]

soybeans are shown in the top right corner, implying high contribution to calorie supply and high environmental costs. However, the caveat here is that the bulk of these imported soybeans is used as livestock feed[128] and the calories ultimately delivered for human nutrition are therefore much lower. At the same time, livestock products such as milk, eggs, and meat have higher amounts of micronutrients per unit weight than cereal crops and help meet the micronutrient demand of the population of importing countries.[54]

RESEARCH FRONTIERS

As shown by this review, global-level datasets increasingly allow for quantifying effects of trade on land systems across multiple sustainability dimensions. The revealed patterns are far from uniform and highly context specific. Methodological advances are needed to translate insights from these global-level studies into concrete policy and governance options on how systems could be adapted to reach more efficient and equitable outcomes. To guide such advances, we here sketch out a number of research frontiers that, if addressed, have the potential to make this relatively young research area more robust and impactful.

1. When studying the effects of trade on human nutrition, studies are increasingly extending the usual focus on macronutrients, such as calories and protein, toward investigations of how trade affects micronutrient availability.[54,129] This should be further extended to cover a complete set of essential micronutrients required for a healthy life. Increasingly available global data on nutrient availability will be a crucial input for advancing this field.[130,131] At the same time, more research is needed to understand in what settings trade is fostering or speeding up a transition toward unhealthy Western dietary patterns.[132] A better understanding of the impacts of trade on nutrient availability for exporting systems will be important, considering the increasing importance of large-scale land acquisitions in the Global South.[63]
2. Studies have focused on the effect of trade on habitat conversion and ecosystem carbon storage, a central function of ecosystems. It will be important to more comprehensively assess how trade alters whole sets of ecosystem functions and services and also how trade benefits from them.[133,134] Recent studies of how trade depends on pollination services in the exporting countries' land systems are an example for such endeavors.[135,136] As it becomes increasingly evident that ecosystem functions and services are interacting with each other and should be assessed in concert,[137] it is important to assess how trade affects ecosystem multi-functionality and stability.
3. Similarly, work on how trade impacts biodiversity will have to pay attention to the multi-dimensional nature of the concept. Most studies so far have focused on the effect of habitat conversion on species richness. Incorporating different biodiversity metrics might be a more encompassing option.[134,138,139] Such metrics could focus on phylogenetic,[98] functional,[140] or structural diversity,[141] to obtain a more comprehensive idea of how agricultural trade impacts biological diversity. In addition, the role of baseline choice, for instance, changes compared with potential natural patterns or changes compared with a year in the recent past, should be explored systematically.[142] Furthermore, going beyond investigating the effects of habitat conversion on biodiversity and carbon dynamics will be crucial: land management, for instance, through pesticide[143] and fertilizer use or landscape configuration,[144] has large effects on human health, biodiversity, and aquatic systems, which are presently not sufficiently captured in global models.[145] Lastly, linking the introduction of alien species, which occurs largely through global transport movements,[146] to the trade and consumption of agricultural products will help to draw a more complete picture.
4. Most of the studies in our review rely on national data for trade flows and consumption patterns. For the impacts in exporting countries, typically a proportional distribution across areas between export production and production for domestic use is assumed.[147] Increasingly, data are becoming available that allow for finer-resolution assessments along various parts of international supply chains.[148] For instance, Escobar et al.[83] and zu Ermgassen et al.[84] provide detailed assessments of how Brazil's production of soybeans and beef is linked to international trade. They find that sourcing patterns of consumer countries differ markedly across a large producer country, and with them the impacts of consumption on producing systems. At the same time, the sectoral resolution of economic models is continuously increasing,[139] and hybrid models that rely on monetary and physical data are being developed.[124,149,150] These models are deemed to be better suited for capturing trade in agricultural products.
5. In addition to refining assessments on the production side, it will be important to assess how consumption patterns are affected by trade beyond national averages. The nutritional benefits brought about by trade might not translate into benefits for certain population groups, as in many

settings there are large discrepancies in food consumption patterns across socio-economic groups or urban rural gradients.[151] Such more fine-tuned approaches can help identify potential points of interventions along specific supply chains.

6. To be more impactful, it will be important to find ways to link global-level studies that we reviewed here across scales to local processes and supply-chain actors. The emerging field of telecoupling research[4] has started to explore tools for such cross-scale integration, building on experience from transdisciplinary land system science.[152] Better data across scales can also inform impact evaluations of trade and conservation policy[153] that can help inform trade policy and facilitate learning from positive examples.

A point that becomes clear from this list is that research has to move beyond disciplinary perspectives and that in many areas progress can only be achieved by knowledge integration across individual disciplines. This is particularly important if we are to provide insights and policy support for managing the trade-offs between environmental and social targets arising from the heterogeneous impacts of agricultural trade.

By showing that trade has both positive and negative sustainability implications, our review has highlighted trade-offs and synergies between nutrition, carbon, and biodiversity impacts. Overall our results indicate that trade can play a positive role in fostering sustainable land use. To achieve this, trade should contribute to, on the production side, minimizing use of land and industrial inputs, while simultaneously securing crop diversity and protecting carbon stocks and biodiversity. On the consumption side, trade flows ideally improve the availability of essential nutrients and reduce the share of land-intensive products in diets that are not required for a healthy diet.

While we found that presently trade links exist, which (partly) contribute to overall positive effects, many trade flows are associated with overall negative effects or with trade-offs between positive and negative sustainability implications. For instance, while the concentration of cereal production in North America has spared land and reduced biodiversity loss compared with a no-trade counterfactual, the increased demand for tropical products fuel by international markets and trade strongly contributes to high levels of deforestation and biodiversity loss, with the traded products often contributing little to improved nutrition in the importing countries.

Again, this calls for acknowledging the multi-dimensionality of the issue and consideration of the local contexts in which trading partners operate. Quantitative assessments of the impacts of global agricultural trade flows across multiple sustainability dimensions, grounded in such an understanding of local context, have the potential to generate a system-wide understanding of how to enhance the positive role international trade can play in addressing sustainability challenges. Such assessments could, for instance, contribute to the development of policy actions to reduce deforestation by providing guidance on commodities and regions to target and by acknowledging potential trade-offs and problem shifts,[154] thus laying the groundwork for stronger sustainability criteria in international trade agreements.[155]

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and queries will be fulfilled by the lead contact, Thomas Kastner (thomas.kastner@senckenberg.de).

Materials availability

Data generated in this study have been deposited at Zenodo, https://doi.org/10.5281/zenodo.5243353.

Data and code availability

Analyses were performed in R 4.0.3. Next to the generated data, all original code for the presented analyses has been deposited at Zenodo under https://doi.org/10.5281/zenodo.5243353 and is publicly available as of the date of publication.

Spatial data of cropland use and crop production

Data on global cropland use (in hectares of physical area) and production (in tons) were available via the latest version of the MapSPAM database,[107] representing the situation in 2010 at the resolution of 5 arcmin. These data differentiate 42 crop types covering the primary crops covered in FAOSTAT and four management types. The data also contain information on the country to which the respective pixel belongs. We reprojected these data to a 10-by-10 km equal area grid (Eckert IV projection) to obtain comparable cell sizes for the crop diversity analysis.

Integration with data on crop product trade and consumption

We then overlaid these maps of crop production and cropland area with data on trade and consumption of crop products. To match the product resolution between MapSPAM and FAOSTAT,[36] we aggregated MapSPAM data on the two coffee crops, the two types of millet, and the two sugar crops, respectively. The trade and consumption data are based on production and trade data from FAOSTAT[36] and are processed with an algorithm that tracks primary and processed crop and livestock products along international supply chains.[75,156] The approach uses physical trade and production, i.e., in tons, converts processed products into their primary crop equivalents (e.g., soybean oil to soybean equivalents), and uses the underlying assumption that, within a country, domestic production and imports contribute proportionally to domestic consumption and exports. For instance, if the Netherlands imports soybeans from Brazil and processes them into soybean oil, which is exported to Germany where it is consumed in food products, these data will show a link between consumption in Germany and soybean cultivation in Brazil. We used the data calculated with this approach from Pendrill et al.[75] and average them for the period 2009–2011 to be in line with the land-use data. We assign export production proportionally to all production areas in a country, except for areas identified to serve subsistence production in MapSPAM[107], which are considered to exclusively serve domestic consumption.

The resulting data were used for the crop diversity analysis (see Box 1) and aggregated to the national level. This gave us data linking countries of crop production with countries where the products processed from these crops are (physically) consumed, along with data on the physical areas required to produce the crops. We converted the data on crop products into caloric equivalents based on factors from FAO.[157]

Integration with data on impacts of crop production on ecosystems

We then linked these data with factors per unit area that quantify the impacts of crop production on biodiversity, deforestation area, and ecosystem carbon.

For biodiversity loss, we apply the national level characterization factors,[108] indicating the number of species potentially lost at the global level (potential global species loss) per square meter of cropland use. These factors are built on a countryside species-area relationship approach,[158] taking into account the extent of habitat conversion through land use and species' abilities to survive in modified habitats. We employ factors for arable land for annual crops and factors for plantations for permanent crops in the MapSPAM data, respectively. The factors originally distinguish three different land-use intensity classes.[108] We use the values for low intensity, effectively excluding the land-use intensity effects on species extinctions, i.e., focusing, in line with our review, on habitat conversion effects. However, in the current implementation, the effect of land-use intensity is limited; using the factors for high intensity would not alter the overall patterns and increases the global total for potential species loss by less than 10%.

In addition, we make use of recently published data to link crop products and crop product trade to deforestation impacts, both in terms of area[75] and in terms of land-use change emissions.[76] These data are based on satellite data on forest loss[88] and on a land-balance model that attributes forest loss, and associated emissions, to expanding land uses. For the data on forgone carbon sequestration we followed the approach developed by Marques et al.,[93] but replaced the land-use data they used with the MapSPAM data[107] and utilized a more recent layer on carbon sequestration potential of land.[159] The hypothetical assumption underlying this perspective is that land currently under use for crop production is taken out of production and left to regenerate. The values presented indicate the average annual carbon sequestration potential over a regrowth period of 30 years, if production ceased for the entire period.

Analyses presented in the article

Based on the compiled data, we performed analyses, which are presented in Figures 2, 3, and 4 as well as Box 1.

National level per capita "net trade" balances

For each country, we aggregated the total imports, respectively cropland use and impacts induced by them, and subtracted the total exports. The resulting values show the "net trade balance" for the respective indicator. We normalized the resulting values by the country's population in 2010.[36] Net imports imply that imports, respectively of resources or impacts associated with them, are larger than the corresponding values for exports, while net exports refer to the opposite situation. For instance, if country A's imports were attributed with a deforestation area of 100 m^2 per capita and year and its exports were attributed with a deforestation area of 60 m^2 per capita and year, the country will be considered a net importer of deforestation area, with a value of $100 - 60 = 40$ m^2 per capita and year. We grouped net importers and net exporters into four groups, respectively, and included a group for balanced "trade patterns." The results of this analysis are presented in Figure 2.

Effects of current trade pattern on global cropland use and associated impacts

To assess the effect that current trade patterns of cropland products have on land demand, biodiversity loss, and ecosystem carbon storage, we compared the situation in 2010 with a counterfactual no-trade situation. This assumes that consuming countries produce all the crops for their consumption, i.e., including imports but excluding exports, domestically, with average domestic yields and average domestic factors for impacts per unit of cropland, assuming land is available for this production if the respective crop is currently already produced domestically. This approach follows the rationale of "global water savings"[106] that is commonly used in assessing global effects of virtual water trade. We stress that this presents a hypothetical thought experiment, and we discuss a number of caveats in the main text that have to be kept in mind when interpreting its results. With this approach, the overall consumption is unchanged but the origin of this consumption is, wherever possible, assumed to be domestically sourced. In cases where the imported crop is not grown in the consuming countries, the approach is not applicable, and here we show the area demand and impacts of the exporting countries (i.e., the same as in the current situation). If the crop is grown in the importing country, and under the counterfactual assumption, two cases can emerge: (1) the domestic impact per unit product is higher than the corresponding value in the exporting country, implying that current trade patterns contribute to avoiding impacts; and (2) the domestic impact per unit product is lower than the corresponding value in the exporting country, implying that current trade patterns introduce additional impacts. We present the results of this analysis in Figure 3, aggregated across crop categories, producing regions and consuming regions, respectively, for the three impact categories. The composition of these aggregates is shown in Tables S2 and S3.

Crop production for exports and associated biodiversity loss and deforestation

In Figure 4 we plot data summed up across crop categories in terms of caloric output versus the totals for biodiversity loss and annual forest loss to visualize how output and impacts align. In addition, we indicate the global area for the production (bubble size) and the share of global production used for exports (bubble color).

Relations between crop diversity and international trade

For the description of this analysis, please refer to Box 1. The categories for the bivariate map are based on quantiles for both the crop diversity measure and the share of area used for export production.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.09.006.

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AUTHOR CONTRIBUTIONS

Conceptualization, T.K., A.C., S.G., A.M., and U.M.P.; writing – original draft, T.K., A.C., S.G., A.M., and U.M.P.; data curation, T.K., G.B., G.L.P., and F.S.; visualization, all authors; writing – review & editing, all authors; project administration, T.K.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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